IfI Technical Reports

Institute of Computer Science,
Clausthal University of Technology

IfI-05-06

Clausthal-Zellerfeld 2005

Strategic Ability under Uncertainty

Wojciech Jamroga[1] and Wiebe van der Hoek[2]

[1]Institute of Computer Science, Clausthal University of Technology, Germany
wjamroga@in.tu-clausthal.de
[2]Department of Computer Science, University of Liverpool, UK
wiebe@csc.liv.ac.uk

Abstract

Modal logics of strategic ability form one of the fields where logic and game theory can successfully meet. This paper reports research in progress on ATOL, a logic designed to capture strategic properties of agents under incomplete information. The notation and terminology, chosen originally for ATOL, were rather unfortunate. Moreover, ATOL needs a large number of modal operators in order to express properties of agents. We rewrite the syntax and semantics of ATOL, using an easier-to-read notation, and more natural terminology. More importantly, we propose an alternative "take" on ATOL, in which simple cooperation modalities can be combined with epistemic operators into sufficiently expressive formulae. This new version of ATOL is no less expressive than the older version, while retaining the same complexity of model checking.

1 Introduction

Modal logics of strategic ability [1, 3, 14, 15] form one of the fields where logic and game theory can successfully meet. The logics have clear possible worlds semantics, are axiomatizable, and have some interesting computational properties. Moreover, they are underpinned by a clear and intuitively appealing conceptual machinery for modeling and reasoning about systems that involve multiple autonomous agents. The basic notions, used here, originate from temporal logic (i.e., the logic of time), and classical game theory [23, 12, 13], which emerged in an attempt to give precise meaning to common-sense notions like choices, strategies, or rationality – and to provide formal models of interaction between autonomous entities, that could be used in further study. Thus, the notions and models were meant to describe real-life phenomena that occur in communities of individual and collective agents (e.g., companies). Of course, the treatment of interaction, given by von Neumann, Morgenstern and Nash, *is* oversimplistic, and its fundamental philosophical merit has also been questioned.[1] One may even ar-

[1]Consider this quote from [19]: "Rational Behavior [is]: greed, modified by sloth, constrained by formless fear and justified *ex post* by rationalization."

gue whether modeling of intelligent agents and their interaction can be done with the tools of mathematics and formal logic at all [24, 16]. However, having a formal model of a problem makes one realize many (otherwise implicit) assumptions underlying his or her approach to this problem. Modal logics that embody basic game theory notions – and at the same time build upon branching-time temporal logics, well known and studied in the context of computational systems – seem a good starting point for investigating multi-agent systems. Therefore we begin our paper with a short presentation of Alternating-time Temporal Logic (ATL) [1, 2, 3], probably the most important logic of strategic ability that has emerged in the recent years.

As ATL addresses games in which agents possess perfect information about the current state of the game, an extension of ATL, called *Alternating-time Temporal Epistemic Logic* (ATEL), was introduced in [20, 21] in order to enable reasoning about agents acting under incomplete information. ATEL adds to ATL the vocabulary of epistemic logic; still, in ATEL the strategic and epistemic layers are combined as if they were independent. They are – if we do not ask whether the agents in question are able to identify and execute their strategies. They are not if we want to interpret strategies as *executable plans*, about which the agents *know* that they guarantee achieving the goal. This issue was first addressed in [7], and investigated in detail in [8]; we give a short summary here in Section 3.

Several updates of ATEL have been proposed to overcome the problem: Alternating-time Temporal Observational Logic (ATOL) and ATEL with Recall (ATEL-R*) in [8], the ATEL version from [9], and Epistemic Temporal Strategic Logic in [22]. In this paper, we focus on ATOL, a logic proposed and discussed by us in [8].

2 ATL: Strategic Ability in Perfect Information Games

ATL [1, 2, 3] was invented to capture properties of *open computer systems* (such as computer networks), where different components can act autonomously, and computations in such systems are effected by their combined actions. Alternatively, ATL can be seen as a logic for systems involving multiple agents, that allows one to reason about what agents can achieve in game-like scenarios. ATL can be understood as a generalization of the well-known branching time temporal logic CTL [4], in which path quantifiers are replaced by so called *cooperation modalities*. Formula $\langle\langle A\rangle\rangle\varphi$, where A is a coalition of agents, expresses that A have a collective strategy to enforce φ. ATL formulae include temporal operators: "$\bigcirc$" ("in the next state"), $\Box$ ("always from now on") and $\mathcal{U}$ ("until").[2] Like in CTL, every occurrence of a temporal operator is preceded by exactly one cooperation modality.

A number of different semantics and model classes has been defined for ATL, most of them equivalent (cf. [5, 6]). In this paper, we use a variant of *concurrent game structures*, which includes a nonempty finite set of all agents $\mathbb{A}\mathrm{gt} = \{a_1, ..., a_k\}$, a

[2] Additional operator $\Diamond$ ("now or sometime in the future") can be defined as $\Diamond\varphi \equiv \top\,\mathcal{U}\varphi$.

nonempty set of states Q, a set of atomic propositions Π, a valuation of propositions $\pi : \Pi \to \mathcal{P}(Q)$, and the set of (atomic) actions Act. Function $d : \mathbb{A}\mathrm{gt} \times Q \to \mathcal{P}(Act)$ defines actions available to an agent in a state, and o is the (deterministic) transition function that assigns the outcome state $q' = o(q, \alpha_1, \dots, \alpha_k)$ to state q and a tuple of actions $\langle \alpha_1, \dots, \alpha_k \rangle$ that can be executed by $\mathbb{A}\mathrm{gt}$ in q. A *strategy* of agent a is a conditional plan that specifies what a is going to do for every possible game history. A *collective strategy* for a group of agents A is simply a tuple of strategies, one per each agent from A. A *path* in M is an infinite sequence of states that can be effected by subsequent transitions, and refers to a possible course of action (or a possible computation) that may occur in the system. Let $\lambda[i]$ denote the ith position on path λ. Now:

$M, q \models \langle\langle A \rangle\rangle \bigcirc \varphi$ iff there is a collective strategy S_A such that, for every path λ that may result from A executing S_A and the agents in $\mathbb{A}\mathrm{gt} \setminus A$ choosing any of their available actions, φ holds in $M, \lambda[1]$;

$M, q \models \langle\langle A \rangle\rangle \Box \varphi$ iff there exists S_A such that, for every λ resulting from execution of S_A, φ holds in $M, \lambda[i]$ for every $i \geq 0$;

$M, q \models \langle\langle A \rangle\rangle \varphi \mathcal{U} \psi$ iff there exist S_A and $i \geq 0$ such that, for every λ resulting from execution of S_A, ψ holds in $M, \lambda[i]$ and φ holds in $M, \lambda[j]$ for every $0 \leq j < i$.

Proposition 1 [3] *The complexity of the model checking problem for* ATL *is linear in the size of the model (i.e., the number of transitions) and the length of the checked formula.*

3 Problems with Strategic Ability under Uncertainty

ATEL [20, 21] enriches the picture with epistemic component, adding to ATL operators for representing agents' knowledge: $K_a\varphi$ reads as "agent a knows that φ". Additional operators $E_A\varphi$, $C_A\varphi$, and $D_A\varphi$ refer to *"everybody knows"*, *common knowledge*, and *distributed knowledge* among the agents from A. Thus, $E_A\varphi$ means that every agent in A knows that φ holds, while $C_A\varphi$ means not only that the agents from A know that φ, but they also know that they know that, and know that they know that they know it, etc. The distributed knowledge modality $D_A\varphi$ denotes a situation in which, if the agents could combine their individual knowledge together, they would be able to infer that φ is true.

Models for ATEL extend concurrent game structures with epistemic accessibility relations $\sim_1, ..., \sim_k \subseteq Q \times Q$ (one per agent) for modeling agents' uncertainty.[3] Agent a's epistemic relation is meant to encode a's inability to distinguish between the (global) system states: $q \sim_a q'$ means that, while the system is in state q, agent a cannot really determine whether it is in q or q'. Then:

[3] The relations are assumed to be equivalences.

$M, q \models K_a\varphi$ iff φ holds for every state q' such that $q \sim_a q'$.

Relations $\sim_A^E$, $\sim_A^C$ and $\sim_A^D$, used to model group epistemics, are derived from the individual accessibility relations of agents from A. First, $\sim_A^E$ is the union of relations $\sim_a$, $a \in A$. Next, $\sim_A^C$ is defined as the transitive closure of $\sim_A^E$. Finally, $\sim_A^D$ is the intersection of all the $\sim_a$, $a \in A$. The semantics of group knowledge can be defined as below (for $\mathcal{K} = C, E, D$):

$M, q \models \mathcal{K}_A\varphi$ iff φ holds for every state q' such that $q \sim_A^{\mathcal{K}} q'$.

One of the main challenges in such a logic is the question how, given an explicit way to represent agents' knowledge, this should interfere with the agents' available strategies. What does it mean that an agent has a strategy to enforce φ, if it involves making different choices in states that are epistemically indistinguishable for the agent, for instance? Moreover, agents are assumed some epistemic capabilities when making decisions, and other for epistemic properties like $K_a\varphi$. The interpretation of knowledge operators refers to the agents' capability to distinguish one *state* from another; the semantics of $\langle\langle A\rangle\rangle$ allows the agents to base their decisions upon *histories*, i.e. sequences of states. These tensions between complete vs. incomplete information on one hand, and perfect vs. imperfect recall on the other, has been studied in [8]. It was also argued that, when reasoning about what an agent can *enforce*, it seems more appropriate to require the agent to know his winning strategy rather than to know only that such a strategy exists. This problem is closely related to the distinction between knowledge *de re* and knowledge *de dicto*, well known in the philosophy of language [17], as well as research on the interaction between knowledge and action [10, 11, 25]. Two variations of ATEL were proposed as solutions: ATEL-R* where agents were able to memorize the whole game by definition, ATOL for agents with (possibly) bounded memory. As agents seldom have unlimited memory, and logics of strategic ability with incomplete information and perfect recall have undecidable model checking [18], we think that ATOL is more important of the two.

4 The Logic of ATOL

We believe that ATOL captures agents' strategic abilities under incomplete information in an intuitive way (cf. Observation 3). However, the notation chosen for the logic in [8], and even its name, were rather unfortunate (the name of Alternating-time Temporal Logic is hard enough to understand; we made it worse by using the term "observation" in a non-standard way). Here, we would like to present the syntax and semantics of ATOL in a more understandable form.

4.1 Syntax

The language of ATOL (with respect to a set of agents $\mathbb{A}\mathrm{gt}$, and atomic propositions Π) can be formally defined as the following extension of ATL:

$$\varphi ::= p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \mathcal{K}_A\varphi \mid \langle\langle A\rangle\rangle_{\mathcal{K}(\Gamma)} \bigcirc \varphi \mid \langle\langle A\rangle\rangle_{\mathcal{K}(\Gamma)} \Box\varphi \mid \langle\langle A\rangle\rangle_{\mathcal{K}(\Gamma)} \varphi\,\mathcal{U}\varphi.$$

where $p \in \Pi$ is a proposition, $A, \Gamma \subseteq \mathbb{A}\mathrm{gt}$ are groups of agents, and $\mathcal{K}$ refers to the collective epistemic operators E, C, D. Again, $\langle\langle A\rangle\rangle_{\mathcal{K}(\Gamma)} \Diamond\varphi$ can be defined as $\langle\langle A\rangle\rangle_{\mathcal{K}(\Gamma)} \top\,\mathcal{U}\varphi$, and we can define individual knowledge with $K_a\varphi \equiv C_{\{a\}}\varphi$. The informal meaning of $\langle\langle A\rangle\rangle_{\mathcal{K}(\Gamma)}\varphi$ is: "group A has a strategy to enforce φ, and agents Γ can identify the strategy as successful for A in the epistemic sense $\mathcal{K}$". Only memoryless uniform strategies are considered; we define these notions formally in the next section.

4.2 Semantics

Formulae of ATOL are interpreted in *concurrent epistemic game structures*:

$$M = \langle \mathbb{A}\mathrm{gt}, Q, \Pi, \pi, Act, d, o, \sim_1, ..., \sim_k\rangle$$

in which $\mathbb{A}\mathrm{gt}, Q, \Pi, \pi, Act, d, o$ are inherited from concurrent game structures, and $\sim_1, ..., \sim_k$ are epistemic accessibility relations for agents $a_1, ..., a_k$. We require that agents have the same choices in indiscernible states: for every q, q' such that $q \sim_a q'$ it is required that $d_a(q) = d_a(q')$. To specify plans, agents use *memoryless uniform strategies*.

Definition 1 *A* memoryless uniform strategy *is a function $s_a : Q \to Act$ for which:*

- *$s_a(q) \in d_a(q)$ (the strategy specifies available actions), and*
- *if $q \sim_a q'$ then $s_a(q) = s_a(q')$ (strategies specify the same choices for indistinguishable states).*

As usually, a collective strategy S_A assigns every agent $a \in A$ with one strategy s_a.

When plans under uncertainty are considered, we will be interested in checking if the goal is satisfied in any *subjectively possible* course of action that may result from an execution of such a plan. Note that, in the general case, different agents can be used to identify and execute the plan. Also, collective agents can identify strategies in different epistemic senses. For example, $\langle\langle A\rangle\rangle_{D(\Gamma)}\varphi$ means that coalition Γ acts as a "headquarters committee": if they share their knowledge with each other, they can prepare a plan for team A to achieve φ. A should be able to execute the plan, so it must be uniform for agents from A.

Definition 2 *The set of computations – consistent with strategy S_A, and starting from state q – that are possible from agents Γ's point of view in epistemic mode $\mathcal{K} = E, C, D$, can be defined as:*

$out_{\mathcal{K}}(q, S_A) = \{\lambda = q_0q_1q_2... \mid q_0 = q \sim_{\Gamma}^{\mathcal{K}} \lambda[0]$ *and for every* $i = 1, 2, ...$ *there exists a tuple of agents' decisions* $\langle\alpha_{a_1}^{i-1}, ..., \alpha_{a_k}^{i-1}\rangle$ *such that* $\alpha_a^{i-1} \in d_a(q_{i-1})$ *for each* $a \in A$*, and* $o(q_{i-1}, \alpha_{a_1}^{i-1}, ..., \alpha_{a_k}^{i-1}) = q_i\}$.

The semantics of ATOL is defined via the following rules:

$M, q \models p$ iff $q \in \pi(p)$, for an atomic proposition p;

$M, q \models \neg\varphi$ iff $M, q \not\models \varphi$;

$M, q \models \varphi \wedge \psi$ iff $M, q \models \varphi$ and $M, q \models \psi$;

$M, q \models \mathcal{K}_A\varphi$ iff $M, q' \models \varphi$ for every q' such that $q \sim_A^{\mathcal{K}} q'$.

$M, q \models \langle\!\langle A \rangle\!\rangle_{\mathcal{K}(\Gamma)} \bigcirc \varphi$ iff there is a collective memoryless uniform strategy S_A such that, for every path $\lambda \in out_{\mathcal{K}}(q, S_A)$, we have that $M, \lambda[1] \models \varphi$;

$M, q \models \langle\!\langle A \rangle\!\rangle_{\mathcal{K}(\Gamma)} \Box \varphi$ iff there exists S_A such that, for every $\lambda \in out_{\mathcal{K}}(q, S_A)$, we have $M, \lambda[i] \models \varphi$ for every $i \geq 0$;

$M, q \models \langle\!\langle A \rangle\!\rangle_{\mathcal{K}(\Gamma)} \varphi \mathcal{U} \psi$ iff there exist S_A and $i \geq 0$ such that, for every $\lambda \in out_{\mathcal{K}}(q, S_A)$, we have $M, \lambda[i] \models \psi$ and $M, \lambda[j] \models \varphi$ for every $0 \leq j < i$.

Remark 2 *Since the epistemic relations are required to be equivalences, the epistemic layer of* ATEL *and* ATOL *refers indeed to agents'* knowledge *rather than* beliefs *in general. As the assumption is not vital to any results presented here, we suggest that this requirement can be relieved if necessary, to allow for reasoning about other kinds of beliefs as well.*

Observation 3 *Formula $\langle\!\langle a \rangle\!\rangle_{K(a)}\varphi$ specifies that agent a has a strategy* de re *to enforce φ. In other words, $M, q \models \langle\!\langle a \rangle\!\rangle_{K(a)}\varphi$ if, and only if, there is an executable strategy s_a for a such that every execution of s_a from state q brings about φ, and agent a knows that this is the case. Thus, a can identify s_a as the strategy that guarantees φ.*

Proposition 4 [18, 8] *The model checking complexity for* ATOL *is NP-hard and Δ_2-easy in the size of the model and the length of the checked formula. The problem is NP-hard already in the case when the language includes no epistemic operators, every formula contains at most one cooperation modality, and the games are turn-based (i.e., agents are taking turns one after another).*

4.3 A New Semantics for Strategic Ability and Knowledge

So far, we have been discussing results already presented in previous papers. In this section, we present an alternative semantics for ATOL, which forms the main new contribution of this paper.

One major drawback of ATOL is that it vastly increases the number of modal operators necessary to express properties of agents. For team A, a whole family of cooperation modalities $\langle\!\langle A \rangle\!\rangle_{\mathcal{K}(\Gamma)}$ is created (in place of a single modality $\langle\!\langle A \rangle\!\rangle$ in ATL) in order to specify who should identify the right strategy for A, in what way etc. It would be much more elegant to modify the semantics of "simple" cooperation modalities $\langle\!\langle A \rangle\!\rangle$

and/or epistemic operators, so that they can be composed into sufficiently expressive formulae. The problem with strategic ability under uncertainty is that, when analyzing consequences of their strategies, agents must consider also the outcome paths starting from states other than the current state – namely, all states that look the same as the current state for them. Thus, a property of a strategy being successful with respect to goal φ is *not* local to the current state; *the same* strategy must be successful in all "opening" states being considered. In order to capture this characteristics of strategic ability under incomplete information, we slightly change the type of the satisfaction relation $\models$, and define what it means for a formula φ to be satisfied in a *set of states* $R \subseteq Q$ of model M.

The language is now exactly the same as the one of ATEL [20, 21]:

$$\varphi ::= p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \mathcal{K}_A\varphi \mid \langle\langle A\rangle\rangle \bigcirc \varphi \mid \langle\langle A\rangle\rangle \Box \varphi \mid \langle\langle A\rangle\rangle \varphi \mathcal{U} \varphi.$$

The models are concurrent epistemic game structures again and, like in the previous section, we consider only memoryless uniform strategies. The set of outcome paths of strategy S_A, starting from the "opening" states R, is defined as:

$out(R, S_A) = \{\lambda = q_0q_1q_2... \mid q_0 \in R$ and for every $i = 1, 2, ...$ there exists a tuple of agents' decisions $\langle\alpha^{i-1}_{a_1}, ..., \alpha^{i-1}_{a_k}\rangle$ such that $\alpha^{i-1}_a \in d_a(q_{i-1})$ for each $a \in A$, and $o(q_{i-1}, \alpha^{i-1}_{a_1}, ..., \alpha^{i-1}_{a_k}) = q_i\}$.

Let $img(q, \sim)$ be the image of state q with respect to relation $\sim$, i.e. the set of all states q' such that $q \sim q'$. The new semantics is given through the following clauses:

$M, R \models p$ iff $q \in \pi(p)$ for every $q \in R$;

$M, R \models \neg\varphi$ iff not $M, R \models \varphi$;

$M, R \models \varphi \wedge \psi$ iff $M, R \models \varphi$ and $M, R \models \psi$;

$M, R \models \mathcal{K}_A\varphi$ iff $M, \bigcup_{q \in R} img(q, \sim^{\mathcal{K}}_A) \models \varphi$.

$M, R \models \langle\langle A\rangle\rangle \bigcirc \varphi$ iff there exists S_A such that, for every $\lambda \in out(R, S_A)$, we have that $M, \{\lambda[1]\} \models \varphi$;

$M, R \models \langle\langle A\rangle\rangle \Box \varphi$ iff there exists S_A such that, for every $\lambda \in out(R, S_A)$, we have that $M, \{\lambda[i]\} \models \varphi$ for every $i \geq 0$;

$M, R \models \langle\langle A\rangle\rangle \varphi \mathcal{U} \psi$ iff there exist S_A and $i \geq 0$ such that, for every $\lambda \in out(R, S_A)$, we have that $M, \{\lambda[i]\} \models \psi$ and $M, \{\lambda[j]\} \models \varphi$ for every $0 \leq j < i$.

We will write $M, q \models \varphi$ as the shorthand for $M, \{q\} \models \varphi$. Note that the interpretation of epistemic operators is slightly non-standard: $M, q \models K_a\varphi$ expresses the fact that φ holds for *all* states indiscernible from q, instead of stating that φ holds for *every* one state separately. This makes an important difference when φ requires a single *global* evidence for all the states from $img(q, \sim_a)$ together (like in the case of $\varphi \equiv \langle\langle A\rangle\rangle\psi$).

Let $\models_1$ represent the satisfaction relation according to the semantic rules from Section 4, and $\models_2$ the satisfaction relation according to the new semantics presented here. The following propositions establish the relationship between the former and the latter version of ATOL.

Proposition 5 *The new semantics is expressive enough to capture the strategic ability from the original semantics of* ATOL*:* $M, q \models_1 \langle\langle A\rangle\rangle_{\mathcal{K}(\Gamma)}\varphi$ *if, and only if,* $M, q \models_2 \mathcal{K}_\Gamma\langle\langle A\rangle\rangle\varphi$*.*

Proposition 6 *The new semantics enables expressing properties that cannot be expressed in the original* ATOL*. For example, formula* $K_a K_b\langle\langle A\rangle\rangle\varphi$ *is not expressible in the original version of* ATOL *for most models.*

Proposition 7 *Model checking is NP-hard and* Δ_2*-easy also for this new version of* ATOL*.*

5 Conclusions

The logic of ATOL was designed to capture strategic abilities of agents under incomplete information, and deal with some problems revealed by previous attempts. In this paper, we re-define ATOL, using an easier-to-read notation, and more natural terminology. More importantly, we propose an alternative "take" on ATOL, in which simple cooperation modalities $\langle\langle A\rangle\rangle$ can be combined with epistemic operators into sufficiently expressive formulae. This new version of ATOL is no less expressive than the older version, while retaining the same complexity of model checking.

References

[1] R. Alur, T. A. Henzinger, and O. Kupferman. Alternating-time Temporal Logic. In *Proceedings of the 38th Annual Symposium on Foundations of Computer Science (FOCS)*, pages 100–109. IEEE Computer Society Press, 1997.

[2] R. Alur, T. A. Henzinger, and O. Kupferman. Alternating-time Temporal Logic. *Lecture Notes in Computer Science*, 1536:23–60, 1998.

[3] R. Alur, T. A. Henzinger, and O. Kupferman. Alternating-time Temporal Logic. *Journal of the ACM*, 49:672–713, 2002.

[4] E. A. Emerson. Temporal and modal logic. In J. van Leeuwen, editor, *Handbook of Theoretical Computer Science*, volume B, pages 995–1072. Elsevier Science Publishers, 1990.

[5] V. Goranko. Coalition games and alternating temporal logics. In J. van Benthem, editor, *Proc. of the 8th Conference on Theoretical Aspects of Rationality and Knowledge (TARK VIII)*, pages 259–272. Morgan Kaufmann, 2001. Corrected version. Available at `http://general.rau.ac.za/maths/goranko/papers/gltl31.pdf`.

[6] V. Goranko and W. Jamroga. Comparing semantics of logics for multi-agent systems. *Synthese*, 139(2):241–280, 2004.

[7] W. Jamroga. Some remarks on alternating temporal epistemic logic. In B. Dunin-Keplicz and R. Verbrugge, editors, *Proceedings of Formal Approaches to Multi-Agent Systems (FAMAS 2003)*, pages 133–140, 2003.

[8] W. Jamroga and W. van der Hoek. Agents that know how to play. *Fundamenta Informaticae*, 63(2–3):185–219, 2004.

[9] G. Jonker. Feasible strategies in Alternating-time Temporal Epistemic Logic. Master thesis, University of Utrecht, 2003.

[10] R.C. Moore. A formal theory of knowledge and action. In J. Hobbs and R.C. Moore, editors, *Formal Theories of the Commonsense World*. Ablex Publishing Corp., 1985.

[11] L. Morgenstern. Knowledge and the frame problem. *International Journal of Expert Systems*, 3(4), 1991.

[12] J.F. Nash. Equilibrium points in n-person games. *Proceedings of the National Academy of Sciences U.S.A.*, 36:48–49, 1950.

[13] M. Osborne and A. Rubinstein. *A Course in Game Theory*. MIT Press, 1994.

[14] M. Pauly. Game logic for game theorists. Technical Report INS-R0017, CWI, 2000.

[15] M. Pauly. A modal logic for coalitional power in games. *Journal of Logic and Computation*, 12(1):149–166, 2002.

[16] R. Pfeifer and C. Scheier. *Understanding Intelligence*. MIT Press : Cambridge, Mass, 1999.

[17] W. Quine. Quantifi ers and propositional attitudes. *Journal of Philosophy*, 53:177–187, 1956.

[18] P. Y. Schobbens. Alternating-time logic with imperfect recall. *Electronic Notes in Theoretical Computer Science*, 85(2), 2004.

[19] M. Shubik. Game theory, complexity, and simplicity. Part III: Critique and prospective. Technical Report 98-04-029, Santa Fe Institute, 1998.

[20] W. van der Hoek and M. Wooldridge. Tractable multiagent planning for epistemic goals. In C. Castelfranchi and W.L. Johnson, editors, *Proceedings of the First International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS-02)*, pages 1167–1174. ACM Press, New York, 2002.

[21] W. van der Hoek and M. Wooldridge. Cooperation, knowledge and time: Alternating-time Temporal Epistemic Logic and its applications. *Studia Logica*, 75(1):125–157, 2003.

[22] S. van Otterloo and G. Jonker. On Epistemic Temporal Strategic Logic. In *Proceedings of LCMAS*, 2004.

[23] J. von Neumann and O. Morgenstern. *Theory of Games and Economic Behaviour*. Princeton University Press: Princeton, NJ, 1944.

[24] T. Winograd and F. Flores. *Understanding Computers and Cognition*. Ablex Publishing, 1986.

[25] M. Wooldridge. *Reasoning about Rational Agents*. MIT Press : Cambridge, Mass, 2000.

Impressum

Publisher: Institut für Informatik, Technische Universität Clausthal
Julius-Albert Str. 4, 38678 Clausthal-Zellerfeld, Germany
Editor of the series: Jürgen Dix
Technical editor: Wojciech Jamroga
Contact: wjamroga@in.tu-clausthal.de
URL: http://www.in.tu-clausthal.de/~wjamroga/techreports/

The IfI Review Board